

**PSFC/JA-10-3**

**Current redistribution in HTS cables made  
from 2<sup>nd</sup> generation tapes**

L. Bromberg, M. Takayasu and P. Michael

MIT Plasma Science and Fusion Center  
Cambridge MA 02139

March 4, 2010

## **Abstract**

The current redistribution in cables made from 2<sup>nd</sup> generation HTS tapes is investigated in carpet-stack cables. In the carpet stack geometry tapes are placed next to each other to build up a cable. Current redistribution in HTS cables is complex because of the built-in insulator that prevents effective current transfer between the tapes.

The effective resistance of the shunts made for improving the current transfer between tapes is investigated. We also calculate the mutual inductance between the different tapes in the cable. The time constants for current transfer are then calculated under different assumptions. The effective time constant for current redistribution in the case of a normal zone is then calculated.

Power dissipation in the current redistribution is evaluated and compared with typical numbers for the cryostat loadings. It is shown that shunting the tapes using distributed superconducting tapes is an attractive solution to the current redistribution. The solution is flexible, and the performance of the system can be optimized through changing the width of shunt and/or the distance between shunts.

## I. Introduction

It would be attractive to provide a cable that has means of bypassing a bad region or a normal zone of one or more tapes. This option is possible in HTS because of the higher thermal stability of the conductor, which allows for increase time to perform the current redistribution before the enough heat has been generated to quench the entire cable.

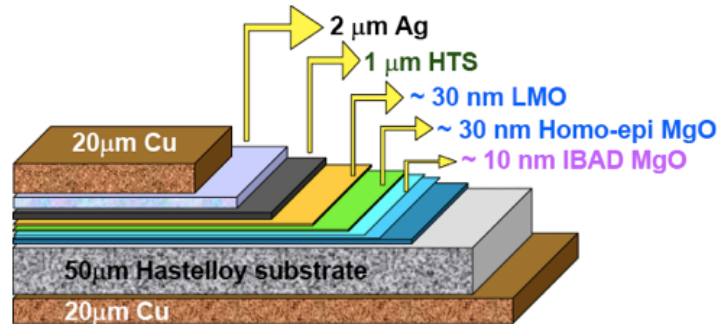


Figure 1. Schematic of the composition of SuperPower 2<sup>nd</sup> generation HTS tapes. Note the presence of multiple insulating layers between the HTS and the substrate

Although the second generation HTS coated conductors do not have the brass layer typical of first generation HTS conductor, in second generation tapes there is an insulating layer beneath the superconductor that prevents current transfer in the direction normal to the tape. The general geometry of the 2<sup>nd</sup> generation tape is shown in Figure 1. Figure 2 shows a microphotograph of the edge of the tape, showing the copper surrounding the HTS/substrate composite. In this report, a preliminary study of the implication of the insulating layer in current redistribution in a stack is presented. This work is needed in order to be able to build a model of the cable that allows the investigation of current distribution (or redistribution after an event) across the many tapes of the cable.

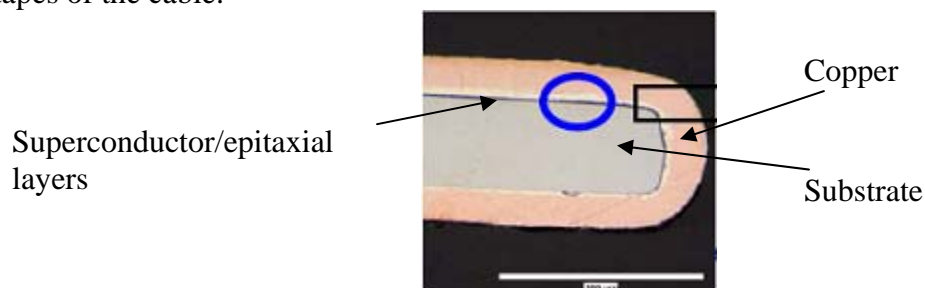


Figure 2 Microphotograph of the edge of the tape, showing the copper surrounding the superconductor and the structure

In the case of Superpower tapes, the copper is electrodeposited. It is assumed that the conductivity of the copper is  $\sigma \sim 4 \cdot 10^8 / \Omega \text{ m}$ . In the models, where there is solder, with a thickness of 20  $\mu\text{m}$  and a conductivity of  $\sigma \sim 6.7 \cdot 10^7 / \Omega \text{ m}$ . It is assumed that the thickness of the HTS layer is 2  $\mu\text{m}$ .

- **Basic Carpet Stack**  
HTS tapes are stacked and twisted together.  
The tapes can be soldered or insulated.
- **Base element former**  
Conducting or non-conducting  
Structural

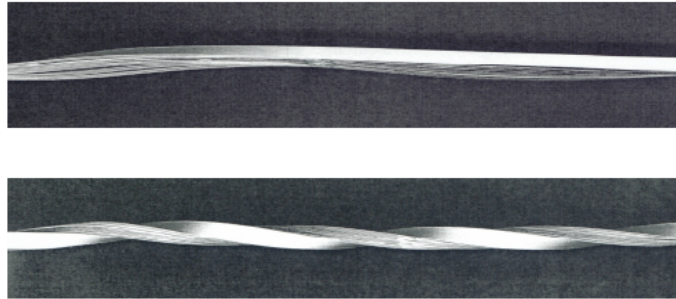


Figure 3 (a). Basic carpet stack geometry, with two different twists. [Takayasu]

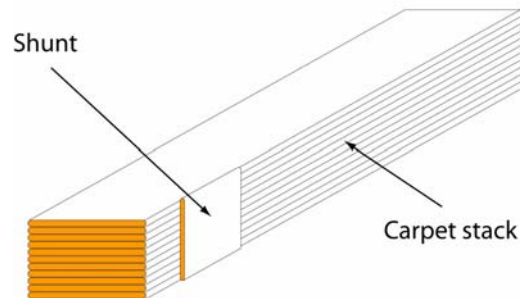


Figure 3(b) Distributed shunt concept investigated in this report. The shunting element is made from a 2<sup>nd</sup> generation tape

This report investigates methods of fabricating the cables to enable current redistribution among the multiple tapes. It is assumed that surrounding the superconductor and substrate there is a copper layer (shown in Figure 2).

The carpet-stack cable [Takayasu] analyzed in this report is shown in Figure 3 shows a picture of a carpet stacked cable, indicating the possibility of twisting of the cable. Multiple tapes are placed next to each other.

## II. Resistance calculation for tape-shunting (carpet stack case)

Three cases are analyzed with respect to the shunting performance of the carpet-stacked case: Unmodified configuration, with conduction through edges of tape

2. Side tape, no solder
3. Side tape, with solder

In the first case the current flows in that section of copper at the edges of the tape, shown in Figure 2.

The different cases are illustrated in Figure 4. Figure 4 (a) shows the unmodified geometry of carpet-stacked tapes, assuming that the tapes are soldered together (case 1). There is a thin solder between the tapes. The substrate, as indicated in the figure, contains multiple epitaxial layers that are insulating, thus we assume that there is no current flowing through the substrate, in particular in the direction normal to the tape. In the direction parallel to the plate, the copper is so much more conducting than the substrate that neglecting its presence is a good approximation.

Figure 4 (b) shows the presence of a tape perpendicular to the stack. The purpose of this tape is to allow tape to tape current transfer with low resistance. The case indicated in Figure 4 (b) shows the soldered stack with a soldered perpendicular tape (case 3). Case 2 is the same as that shown in Figure 4 (b) with the exception that the solder for the perpendicular tape has been eliminated.

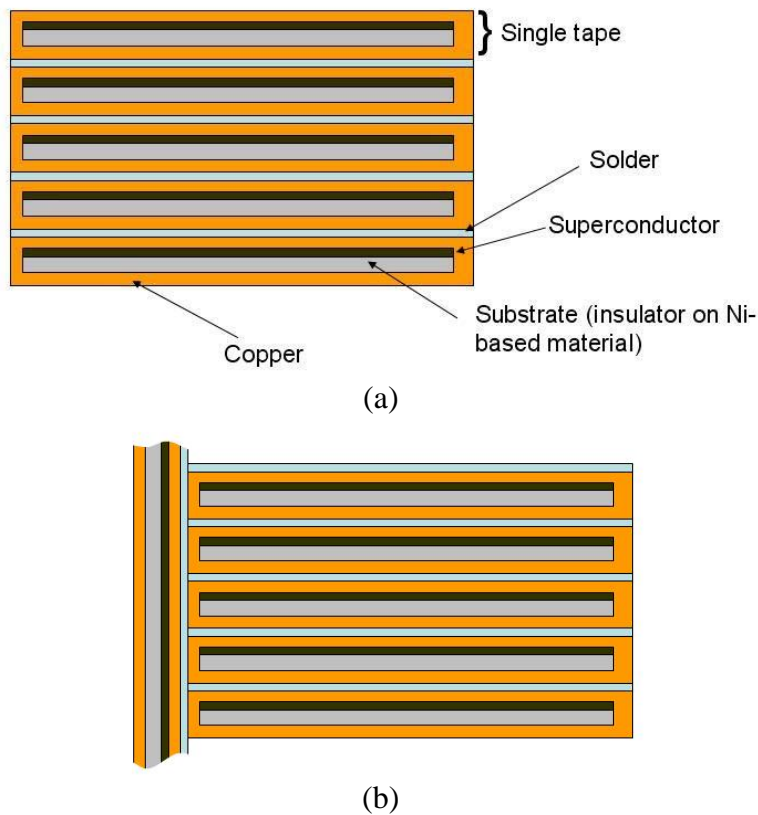


Figure 4. Schematic diagram of a HTS cable made in carpet stack geometry (a) carpet stack with solder between tapes (b) Same as (a) but with the addition of a tape on the side of the HTS stack, soldered to the stack.

1) No side tape, with solder (case 1)

The case of no side tape has the current flowing through the edges of the tapes, where there is no insulation (there is an insulating layer between the superconductor and the poorly conductive substrate, as shown in Figure 1). The current density in the superconductor is assumed to be  $2.5 \cdot 10^{10} \text{ A/m}^2$ , in a tape that is  $2 \text{ }\mu\text{m}$  thick. This corresponds to 100 A. It is assumed that the contact is established in a zone that is 4 mm wide, with the results scaled by this number.

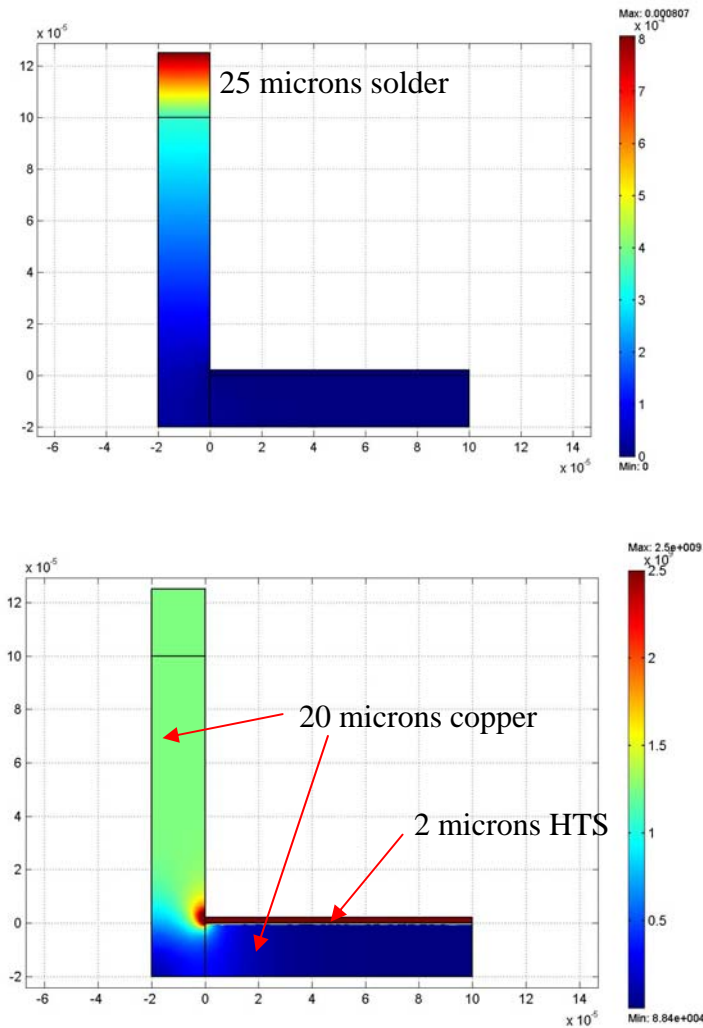


Figure 5 Current density and potential in the case of no side tape.

Because of the high resistivity underneath the HTS layer (shown in Figure 1), the current has to flow on the edges. There is a 20 micron thick layer that covers the HTS tape [SuperPower], including the sides. The current shunts through the conducting copper section at the side; this is the first geometry being considered, with multiple tapes soldered to each other.

The results are shown in Figure 5. The top graph shown the contours of constant current, while the bottom graph shows equipotential contours. The voltage drop per tape period is  $770 \mu\text{V}$ , corresponding to a resistance per tape period of  $\sim 8 \mu\Omega$ . Most of the voltage drop (two thirds) is across the solder. For 40 tapes, the maximum resistance (from the bottom to the top tapes) is  $0.3 \text{ m}\Omega$ .

## 2) Case with side tape, no solder

Figure 6 shows the case with side tape, no solder. In this case, a tape is placed perpendicular to the other tapes in the cable shown in Figure 4 (b) shunting the current from one tape to any other tape in the cable in contact with the superconducting shunting tape. The model includes the copper at the side of the tapes, the copper on top of the shunting tape, but no solder in-between.

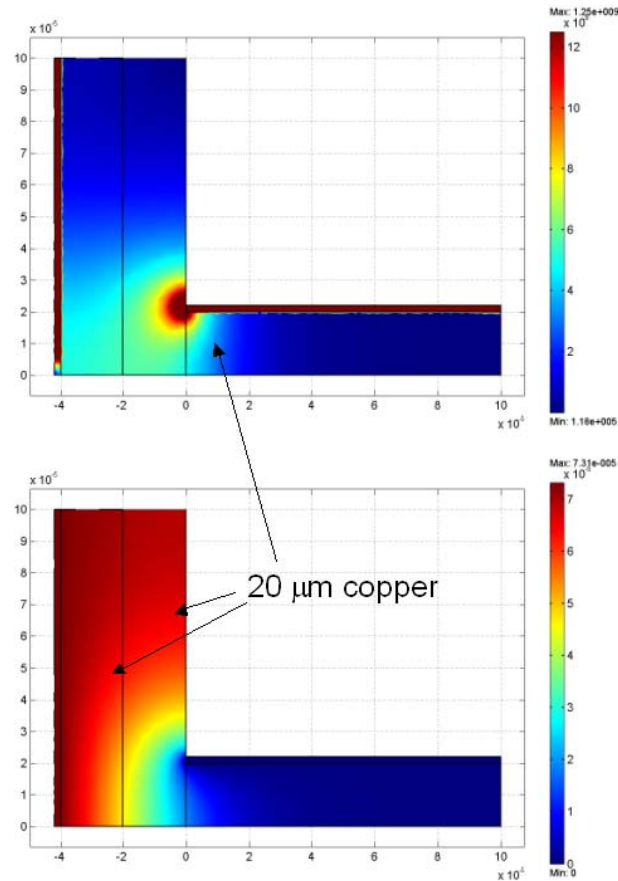


Figure 6 Results for the case with a side tape, no solder.

The results are shown in Figure 6. The same parameters of current density, thicknesses and conductivities and in Figure 5 are assumed, including the thickness of the contact (4 mm, or the width of one tape). In this case, the voltage drop is decreased to  $73 \mu\text{V}$ , and the resistance per tape period is  $0.7 \mu\Omega$ . There is not voltage buildup in this case, as

opposed to the previous case. Not surprisingly, most of the voltage drop is across the first copper region, that is, where the edge of the superconductor meets the side copper.

As it is expected that all the tapes are shunted by the side tape, the maximum resistance is then  $1.4 \mu\Omega$ , (the current needs to be transferred to the superconducting side tape and then back to the other tape, or twice the value calculated in Figure 6) about 3 orders of magnitude lower resistance.

### 3) With side tape and solder

The last case analyzed is similar to the previous case, but it has solder between the cable and the shunting tape. The model and results are shown in Figure 7

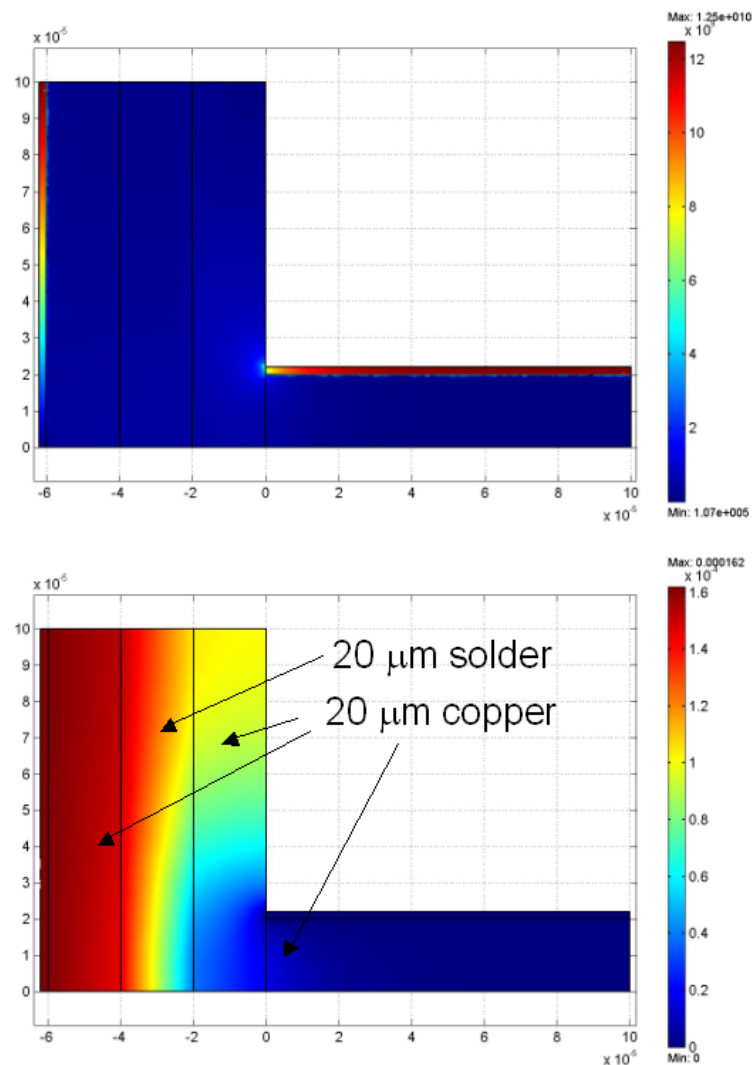


Figure 7. Case with a shunting tape, with solder between the shunting tape and the HTS cable.



The parameters are similar to those of the previous cases, with the exception of a solder layer 20 mm thick, in between the cable and the shunting tape. It should be stressed that in all these cases care must be taken to insure that the shunting tape had the insulating layer on the side of the shunting tape that faces AWAY from the cable.

In this case, the single voltage drop is 162  $\mu\text{V}$  (from one of the tapes to the side shunting tape), with a shunting resistance of about 1.6  $\mu\Omega$ . Thus, the presence of the solder increases the resistance by about a factor of 2, as the current density at that location has been substantially decreased.

In summary:

- The presence of the tape on the side decreases the resistance from the bottom of the stack to the top of the stack by a factor of about 200 (normalized to 4 mm wide contact, same as the tape width)
  - 3  $\mu\Omega$  vs 320  $\mu\Omega$
- This effect is due to the fact that the tapes are separated by multiple, thin insulation layers from the substrate, but even if they would not be present, the substrate is thick and highly resistive, and there are layers of solder between the tapes

### III. Inductance calculations

In this section, the inductances of the tapes in a carpet-stack geometry are discussed.

In order to calculate the inductances, tapes in the carpet stack configuration have been modeled. A 2-D geometry is sufficient, as twists or finite bending radius of the cable will be small compare with the cross sectional dimension of the cable, and thus can be modeled as infinitely long. The tapes are assumed to consist of 2 micron conducting thickness. The rest of the material is neglected, although it could be included to model the magnetic properties of the substrate. For the tapes from SuperPower, the substrate is Hastelloy, which is non-magnetic. The substrate for the AMSC tapes is W-Ni alloy substrate, which is magnetic.

The calculations are performed assuming that the width of the tapes is 3.4 mm. They are arranged in a carpet-stack configuration. The calculation are performed for adjacent tapes (that is, tapes that are next to each other), as well as tapes that are separated by a number of tapes.

The calculations are performed with the commercially available code VectorFields, using release 12.

The field profile in the case of adjacent tapes, 10 tapes in-between tapes, and 40 tapes in-between tapes are shown in Figure 8. In the first case, the tapes are next to each other. Because of the copper, solder and substrate, there is a volume in-between current carrying layers, which has a relatively uniform field (in red in figure 8 (a)). Figure 8 (b)

shows the case of the two tapes of interest, separated by 10 other tapes. In this case, the field is no longer relatively uniform in-between the tapes, and the field starts to “squeeze out” from the region in-between the tapes. For the case of 40 tapes in-between the two tapes of interest, shown in Figure 8 (c), the field does escape substantially. The non-symmetric patterns are due to meshing issues, due to the very large differences in scale length: the current-carrying layers that are 2 microns thick, while the tape widths that are 3.4 mm wide (a factor of about 1000). Figure 8 is drawn with 100 A in each tape, the two tapes having current flowing in opposite directions (no net current). This arrangement is appropriate to determine time scales of current sharing, which is similar to the decay time of “loop” currents.

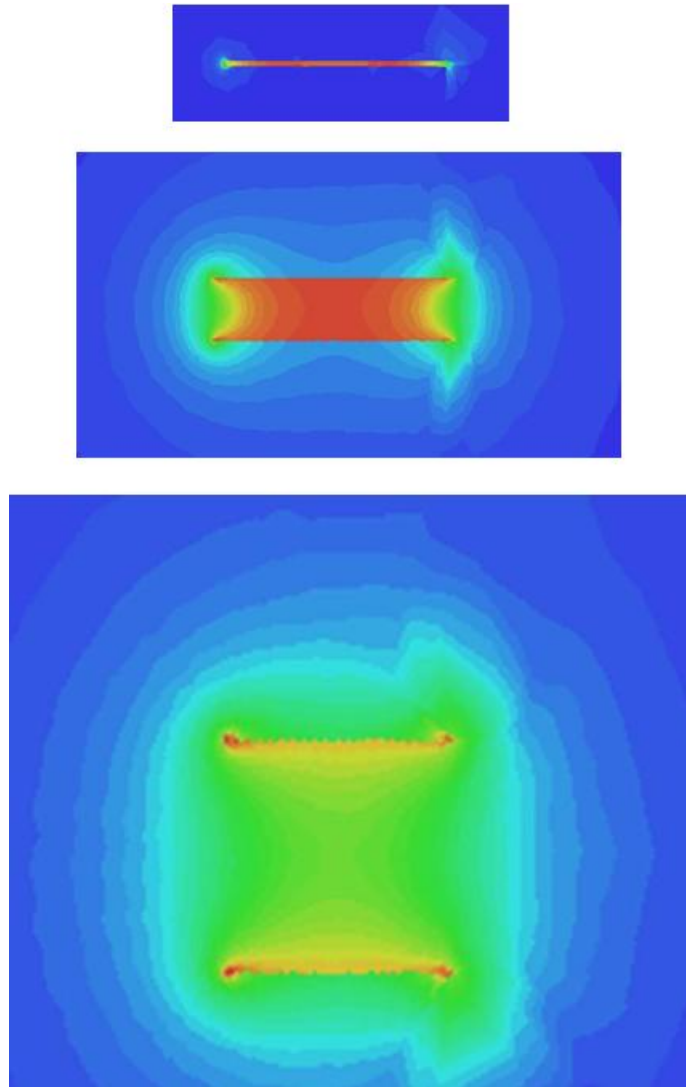


Figure 8. Contours of constant magnetic field distribution in the case of (a) adjacent tapes; (b) 10 tapes; (c) 40 tapes.

The calculations provide information on the energy density per unit length (meter). Using this information and the current flowing per tape, it is possible to calculate the mutual inductances

Figure 9 show the calculated value of the mutual inductance. The values are shown in Figure 9, as a function of the number of tapes in-between the two tapes of interest.

As the distance between the tapes of interest increases, so does the value of the mutual inductance. However, the increase is not linear.

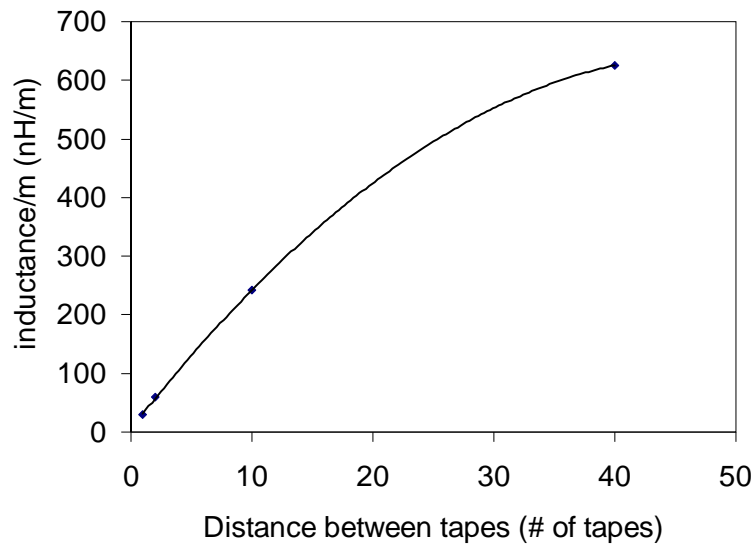


Figure 9. Calculated value of self-inductance for loops in tapes with a given number of tapes in-between.

#### IV. Current transfer time constant

With the information at hand, it is possible now to determine the time required for transfer. The inductance per meter is on the order of 400 nH/m. The resistance due to a single tape (width ~ 3.4 mm) at both ends of the loop in question is  $3 \mu\Omega$  as the current transfer takes two shunts at both ends. Thus, the natural L/R time constant is about 0.13 s/m for 1 tape.

The calculation above used the shunt resistance. In practice, the current redistribution will be driven by the normal zone in one of the tapes. Let's assume that the normal zone in one of the tapes is 0.01 m. It is known that normal zones do not propagate fast in HTS conductors, in part because of the high heat capacity of the metal at the temperatures of operation of HTS materials. Assuming that only the copper next to the superconductor carries any current in the region next to the normal zone (the resistivity is too high to make it to the other side of the tape in the short distance of the normal zone, as shown in the section above). In this case, the cross section of copper carrying current is  $\sim 2.5 \cdot 10^{-8} \text{ m}^2$  (20 microns thick by 0.0034 m wide), with a resistance of 0.3 m $\Omega$ . The cross

sectional area would be increased by a factor of 2 if the copper on the other side of the substrate is included, with a factor of 2 decrease in the resistance. With this resistance, the L/R time for redistribution is about  $10^{-3}$  s per meter cable length between shunts. For a 20 m cable, the time constant is about 20 ms. Even for 200 m between shunts, the current transfer time is 200 ms.

## **V. Power dissipation.**

The shunt resistance can be made very small by increasing the length of the shunt (along the cable), which in the discussions above was limited the width of a tape. In the case of a single-tape wide shunt the DC power dissipated if the shunt is one-tape long is 15 mW. More energy is dissipated during short transients or in the case of AC applications.

The dissipated power could be further decreased, if desired, by making the length of the shunt longer than the width of the tape. The power is small enough so that a number of current transfers can be accommodated before the resistive losses in the cable approach the value of the cryostat losses, which are  $> 1$  W/m.

## **VI. Summary**

The simple calculations shown in this report indicate that placing shunts along the cable can provide sufficient flexibility to address the problem of current transfer and redistribution in carpet-stacked cables made from 2<sup>nd</sup> generation HTS tapes.

It should be noted that the proposed approach (with distributed shunts) is attractive when the cable is not soldered together along all its length, which would make the cable difficult to handle due to rigidity. Instead, the cable needs to be soldered to the side tapes (and maybe together, if desired) in the region of the shunts.

A detailed calculation of the current transfer, including multiple parallel circuits and dynamics of a normal zone in the HTS cable has yet to be done.

## References

[Takayasu]. Takayasu, M., J.V. Minervini and L. Bromberg, *Superconducting Cable*, US patent application (2008)

[SuperPower] <http://www.superpower-inc.com/>

]VectorFields] <http://www.vectorfields.com/>